Allometry Between Measures of Body Size and Shape in a Large Population-Based Cohort

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Abstract

Traditional manual anthropometrics have been used extensively in practice to derive indicators of health risk, such as growth disorders or obesity; however, these approaches typically reduce the complex shape of human bodies to a series of simple size measures. Three-dimensional (3D) imaging systems capture detailed and accurate images of human morphology which have the potential for use within health applications. However, previous studies utilising 3D imaging have only assessed body shape based on combinations and relative proportions of large numbers of size measures. Geometric morphometrics - established mathematical methods within the fields of anthropology and evolutionary biology - analyse morphological variation and allometric relationships between the size and shape of organisms. The aim of this study was to investigate allometry between traditional measures of body size and novel measures of body shape. Developed analytical procedures were utilised to extract scale-invariant features of torso shape from 3D imaging data of 4,405 male participants in the LIFE-Adult cohort, obtained using a Vitus Smart XXL laser scanner. Partial least squares regression (PLSR) models were created to determine how human body shape changes with increases in body size. This study demonstrated that linear combinations of size measures can explain between 3.2 - 84.4 % of the variation in individual body shape features. These results indicate that measures of human body shape show a complex dependence on body size, providing complementary anthropometric features of the human body. The aim of future studies will be to investigate the efficacy of these measures in clinical epidemiology.

Keywords: Anthropometry, Body shape measurement, Allometry, Epidemiology

1. Introduction

Anthropometry is the scientific study of the measures and proportions of the human body, which are an important source of information for a wide range of scientific fields and applications, including the identification of health risk factors in epidemiological studies [1–3] and apparel sizing [4,5]. Traditional anthropometric techniques rely on tape measures and callipers to acquire lengths, breadths, skinfolds and girths of the body, with combinations of these used to create proxies of weight status and body shape, such as the body mass index (BMI) and the waist-hip ratio (WHR). In clinical practice BMI is the most commonly used measure to determine the healthy weight range for individuals based on their height, but is prone to misclassifying muscular individuals as being overweight or obese [6,7]. Size measures, such as sagittal diameter, waist girth, or waist girth divided by height$^{0.5}$ (WHT.5R) [8], showed improved correlations with quantities of abdominal visceral fat and greater associations with metabolic disease risks compared to BMI [9]. Measures, such as the WHR, provide information about the size of the abdomen relative to the rest of the body, so has been used as a proxy of torso shape and central obesity [7]. However, these relatively simple approaches to measuring the human body are prone to observer error and limited by their simplicity, as they do not fully describe the complex variations in human body shape [10–13].

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3D imaging systems capture detailed and accurate 3D images of the human body from which size and shape characteristics can be extracted. Measures obtained from 3D imaging have been used to describe, interpret and analyse the human body for applications, such as apparel sizing [14,15], and considering risk factors in epidemiological surveys [10,12,16], for the purpose of clinical evaluation and health monitoring [12,17,18]. Due to the rapid and repeatable acquisition of 3D imaging data, previous studies have been able to collect measures from large cohorts of participants [10,19,20], allowing researchers to consider individuals with a wide range of body characteristics. However, measures typically derived from 3D scan images to describe body shape have predominantly been combinations of simple lengths and girths, adopted from the context of clothes sizing [21] and commonly used health indices, such as the WHR [19,20]. Recent studies by Loffler-Wirth et al. [10] and Pluess et al. [22] are the most sophisticated of these, demonstrating the use of machine learning techniques to evaluate large numbers of body size measures and establish clusters of individuals exhibiting similar traits. However, this approach has been criticised as it does not utilise the full potential of 3D imaging and discards the shape information captured by these systems [23].

Shape analysis is the process of understanding and describing the diverse morphological variability within a population, as well as its causes and is fundamental within biological research [24]. However, until recently the study of shape has been mostly descriptive, using simple terms to classify the shape of organisms [25,26]. Geometric morphometrics (GM) are established mathematical methods within the fields of anthropology and evolutionary biology to analyse variations in shape [27]. These methods are founded in shape theory [28] and a conceptual understanding of mathematical shape, defined as *"what is left when the differences which can be attributed to translations, rotations, and dilations have been quotiented out"* [29] (p82). Therefore, to analyse human body shape according to this definition, the effects of non-shape variation - location, rotation and scale - must be removed, which can be achieved using Procrustes superimposition procedures [27]. Allometry investigates the dependence of a body's shape on its size and is commonly used in biology to determine the expected change in shape per unit increase in size within species [30–32]. Allometric scaling is generally the null hypothesis of these investigations, suggesting that when body size increases its shape must also change in a compensatory fashion to preserve function and is a dominant factor contributing to morphological variation [30,32,33]. The aim of this study was to investigate allometry between traditional measures of body size and scale-invariant measures of body shape, obtained using 3D imaging and geometric morphometrics. The objectives were to: characterise the size and shape of individuals within a large cohort using developed analytical procedures and to study the inter-dependence of measures of torso size and shape.

2. Method

2.1 Participants

Data analysed in this study was provided by the Leipzig Research Centre for Civilization Diseases (LIFE), consisting of 3D imaging data and extracted measures of 4,405 male participants (aged 58 ± 13 years, height 176.1±7.3 cm, mass 86.0±14.5 kg, BMI 27.6±4.2 kg/m^2) collected in the LIFE-Adult cohort study. LIFE-Adult is a population-based cohort study, which collected phenotype data of over 10,000 randomly sampled individuals from the city of Leipzig, Germany, covering a main age range from 40-79 years of age, with only a subset of 400 participants aged 18-39 years [2]. Details of the study can be found in Loeffler et al. [2]. As a prerequisite to enrolment, written informed consent was obtained from all participants. The LIFE study was approved by the ethics board of the Medical Faculty of Leipzig University. All procedures and documents for this study were approved by the Sheffield Hallam University Research Ethics Committee, reference number ER13534279.

2.2 Body measurement protocol

3D body scans of participants within the LIFE-Adult cohort were acquired using the Anthroscan Vitus XXL system, comprising the commercial Vitus Smart XXL 3D laser scanner and Anthroscan ScanWorX software (version 2.9.9.b, Human Solutions GmbH, Heidelberg, Germany), in accordance with ISO 20685-1:2018 standards [34]. Details of the full experimental protocol are described in [2]. Participants were advised to stand with feet shoulder width apart, arms spread with elbows slightly bent while making fists with their hands (Figure 1). Body size measures (lengths, girths and angles) were automatically extracted from each scan image using the Anthroscan ScanWorX software. These extracted body measures were based on the location of anatomical landmarks determined by proprietary automatic landmark identification algorithms within the Anthroscan ScanWorX software.

Previous studies conducted by researchers at Leipzig University have shown that these automatically extracted body measures demonstrate good agreement with manual body measures (overall concordance correlation coefficient (OCCC) > 0.77) [35].

2.3 Data analysis

2.3.1 Definition of region of interest

It has been suggested that the torso segment is the section of the body that has the greatest potential for variability in size and shape between participants, due to considerable variations in the types and amounts of tissue present within this region [36,37]. For this reason, it was decided that the torso would be the region of interest for the purposes of this investigation. A modified version of the lower trunk segment proposed by Wicke [37] was used to define the limits of the torso, as the area encompassed between the xiphoid process and the buttock landmark (Figure 1). The buttock landmark corresponds to the gluteal (hip) girth location, as defined by ISAK guidelines: "*The gluteal girth is taken at the level of the greatest posterior protuberance of the buttocks*." [38] (p84). This was used as the inferior boundary of the torso segment due to its being identified reliably within the Anthroscan ScanWorX software and to prevent issues with scan segmentation due to occlusion at the perineum (crotch), caused by variations in participant posture and adiposity level. The xiphoid process landmark was chosen as the superior boundary of the torso segment to prevent potential complications in scan segmentation caused by occlusion in the axilla (armpit) region. However, locating the xiphoid process requires manual palpation and was therefore not possible using the automatic landmark identification algorithms within the Anthroscan ScanWorX software. Through experimentation using 3D scan data of individuals collected in previous investigations, which included the locations of manually palpated anatomical landmarks, the xiphoid process was found to be approximately 60±1.5 % of the proportionate vertical distance between the buttock and neck height landmarks identified within the Anthroscan ScanWorX software (Figure 1). This provided a suitable method for determining the inferior and superior boundaries of the torso region of interest for scan segmentation.

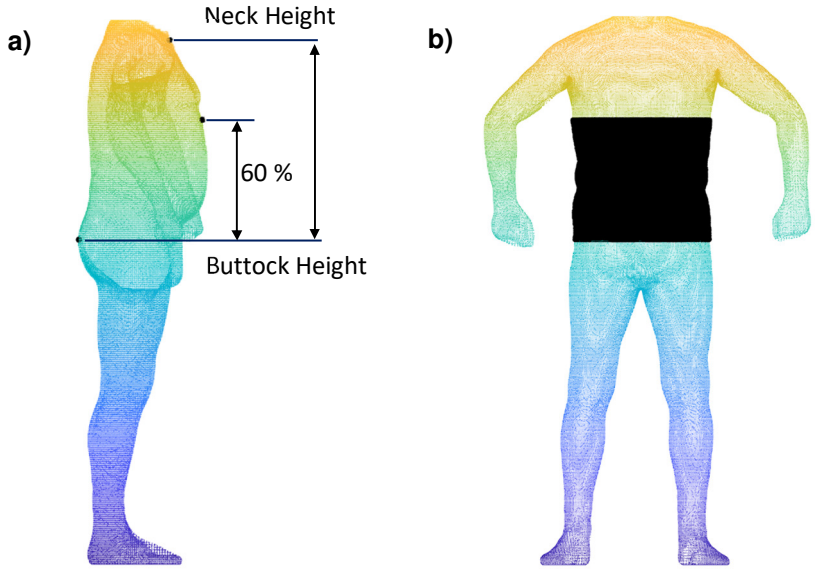

Fig. 1. Participant scanning posture a) side profile b) front profile. The torso segment region of interest is marked on a typical 3D body scan acquired from the Vitus Smart XXL laser body scanner.

2.3.2 Processing of extracted body size measures

All extracted size measurements which related to body segments outside of the torso region of interest, (e.g. ankle height or upper arm length) were removed from the raw data matrix. The resulting data matrix consisted of 34 body size measures for each participant (Table 1). To facilitate comparisons between individuals of differing heights, the torso size measures of each participant were normalised by height. Finally, these height normalised torso size measures were converted into z-scores, providing a common scale in units of standard deviations from the mean.

2.3.2 3D imaging data post-processing

Each body scan within the LIFE-Adult cohort was then processed using a developed analytical procedure for removing non-shape variation in human body scan data [39]. The positions of anatomical landmarks identified on the surface of the 3D body scans were used to create a local coordinate system located at the centre of each scan image according to the convention defined in ISO 20685-1:2018 [34]. The centre of the torso was defined as the midpoint between the xiphoid process on the anterior torso aspect and a landmark on the posterior torso aspect. A vector from the anterior landmark to the posterior landmark identified on the surface of the 3D scan was used as the sagittal axis of the local coordinate system. In the absence of reliable landmarks on the lateral aspect of the 3D scan, the cross product of the sagittal axis and an angled vector on the same transverse plane was used to define the longitudinal axis, assuming that the participant was stood parallel to the global vertical axis. Finally, the cross product of the sagittal and longitudinal vectors defined the transverse axis for each body scan. This anatomical axis system ensured differences in location and orientation between participants in the LIFE-Adult cohort were removed during data processing.

Following alignment each body scan was segmented to include only the coordinate points relating to the region of interest between the xiphoid process and buttock markers (Figure 2a). Twenty-five separate 2 mm bands of data points were extracted from each torso point cloud at uniform intervals along the torso segment. The height of each data slice was set at 2 mm to ensure that the external shape features of the torso segments were preserved while allowing for any gaps in the point cloud, based on a previous study by Clarkson et al. [40]. The raw data points within each slice were collapsed to two-dimensions, creating individual shape profiles along the length of the segment (Figure 2b). The centroid size (square root of the sum of squared distances of landmarks from the centroid) [27] of all extracted shape profiles within each torso was scaled by a single scale factor so that the sum of distances from each point to the centroid for all slices along the torso segment was equal for all participants. This removed any differences in scale between participants, enabling the analysis of torso shape according to statistical shape theory.

Cubic smoothing splines [41] were calculated for each data slice profile along the torso segment. A method for extracting sets of numerical features from a closed curve, based on a previous study by Zahn and Roskies [42], was used to extract the Fourier coefficients that describe the shape of each extracted data slice profile along the length of the torso segment. The polar coordinates within each profile, plotted as a continuous signal waveform (Figure 2c), were inputted to the fast-Fourier transform algorithm in MATLAB (version 9.2, Mathworks, Natick, USA) to extract the frequency components present within each data slice (Figure 2d). Through experimentation it was determined that the higher frequency content within each extracted data slice profile was low amplitude noise and that only the first 10 frequency coefficients were required to reconstruct the features of each original signal waveform curve. This procedure reduced the total number of variables representing each participant to 250 complex Fourier coefficients. Principal components analysis (PCA) was carried out to detect independent features of torso shape that exhibited the highest variation in the sample. This procedure produced a feature vector to characterise the torso shape characteristics of each participant. Scan data post-processing and feature detection procedures were performed using MATLAB (Mathworks, Natick, USA).

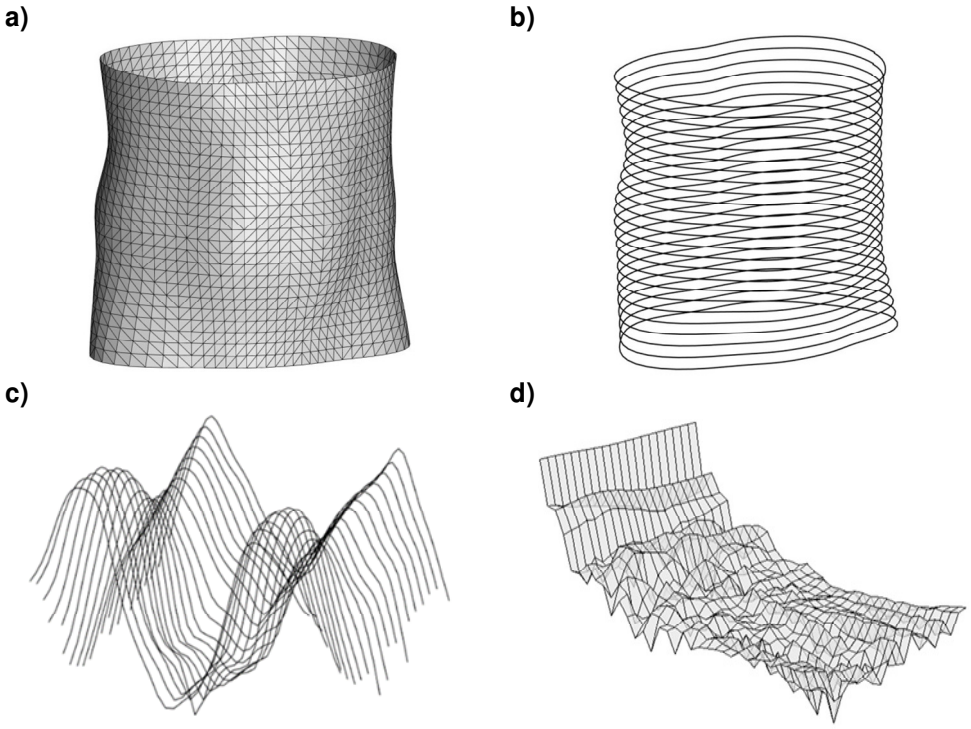

Fig 2. Analytical procedure for extracting shape features from 3D scan data; a) Segment, scale and rotate torso segment; b) Extract transverse data slice profiles; c) Obtain signal waveforms from data slice profiles; d) Extract frequency content from signals. Adapted from [39].

2.4 Statistical analysis

Allometry was examined using partial least squares regression (PLSR) models to determine how identified torso shape principal components depend on measures of torso size. Since the identified torso shape principal components are orthogonal, separate PLSR models were created for each shape principal component, according to recommendations by Wold [43,44], with all torso size measures used as predictor variables. PLSR analyses were conducted within MATLAB using the plsregress MATLAB library source code. The mean squared prediction error (MSEP) by 10-fold cross-validation was calculated to determine the number of components required for each PLSR model, preventing overfitting of the model ensuring the same data are not used to fit a model and estimate prediction error. To determine the importance of each size measure within each PLSR model the variable importance in projection (VIP) statistic was calculated. VIP is the weighted sum of squares of the PLSR-weights, with the weights calculated from the amount of Y- variance of each PLSR component [43,45]. Wold [43] previously suggested that predictor variables demonstrating a VIP ≥ 0.8 can be considered to significantly contribute to the model and have high predictive power. VIP's were calculated within MATLAB, using libPLS [46] MATLAB library source codes. An allometric model was created to assess trends between measures of body size and shape within the LIFE-Adult cohort. Utilising strong correlations between individual torso size measures, PLSR models were created to estimate changes in the complete set of measures from unit changes in waist girth, the measure of torso size most commonly used in clinical practice. Using coefficients from the previously calculated PLSR models between size and shape, changes in torso shape were estimated according to changes in torso size measures, across the range of waist girth measures within the LIFE-Adult cohort, with height held constant at 180 cm.

3. Results

3.1 Torso shape features within LIFE-Adult cohort

The first 9 principal components described 90.4% of the total torso shape variation in the LIFE-Adult cohort. Each of the subsequent principal components accounted for less than 1% of the variance in torso shape. Figure 3a shows the meshed surface image of the average torso shape calculated from all participants in the cohort. Figure 3b shows the maximum deviations from the average torso shape of the sample along each of the first 6 principal components in the positive and negative directions. Blue and red regions on the images represent areas that protrude less, or more than the average torso shape of the cohort, respectively.

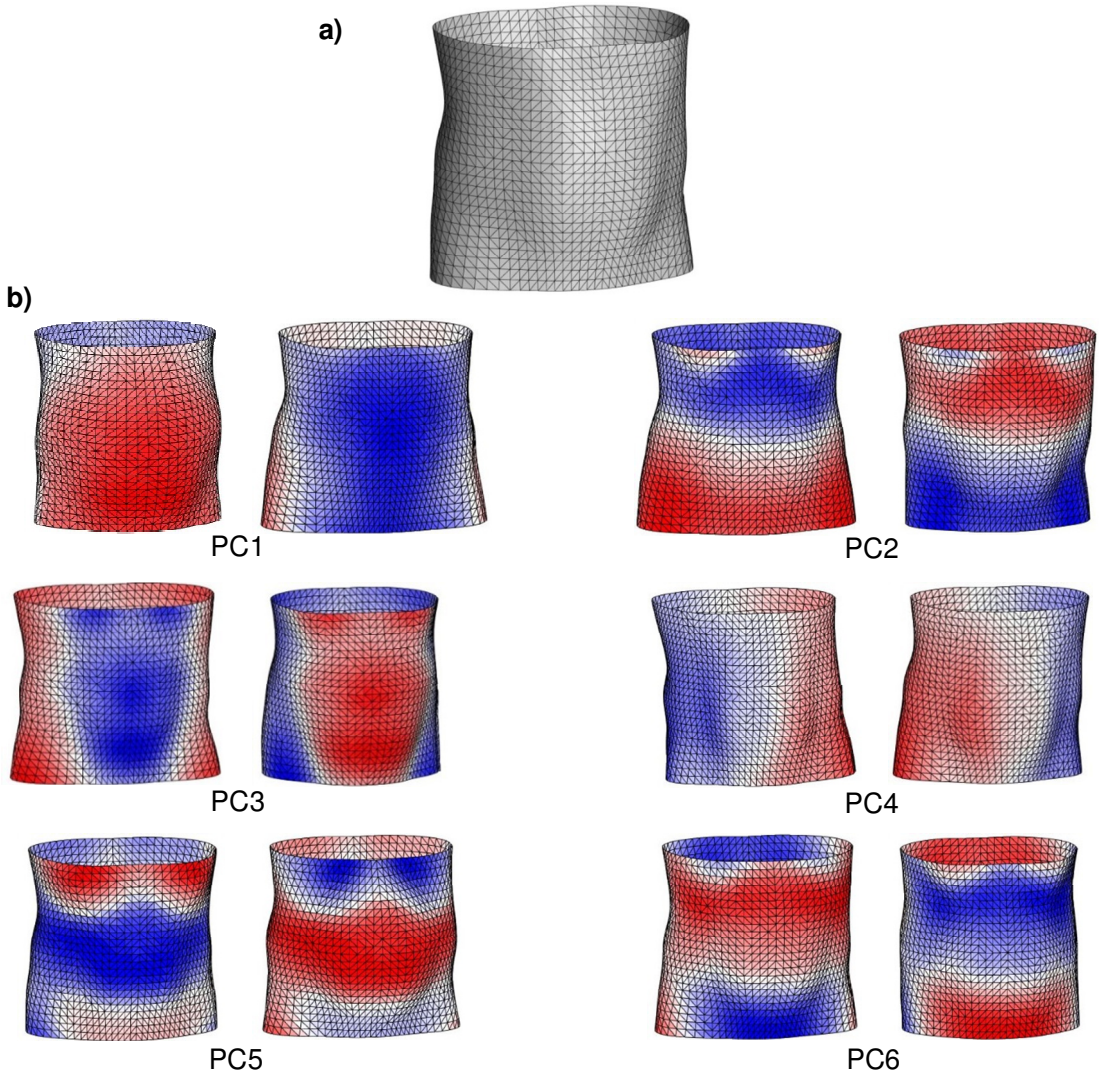

Fig 3. Visualisation of extracted torso shape features; (a) Average torso shape; (b) Deviations from the sample mean along the first 6 principal components. Blue and red regions represent areas that protrude less, or more than the average torso, respectively.

3.2 Allometry between torso size and shape

Table 1 shows the VIP values for the predictor size variables used within each PLSR model. Between 44-65% of body size measures demonstrated VIP values ≥ 0.8 in any of the calculated PLSR models. Table 1 also shows the variation in each identified torso shape principal component which can be explained by combinations of the extracted torso size measures. 84.4% of variance in shape PC3 was explained by changes in torso size. In contrast, only 3.2% of variation in shape PC 4 was explained by torso size measures, since this feature appears to primarily represent asymmetric variations in participant posture (Figure 3b) and is therefore independent of body size.

Table 1. Variable importance in projection (VIP) statistic scores for size measures used as predictor variables in the PLSR models and the percentage of variance in each torso shape principal component explained by size.

	Shape Principal Components								
	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9
Shape PC variation explained by size	64.9%	57.9%	84.4%	3.2%	66.5%	42.5%	56.8%	15.2%	38.3%
Size Measures									
Weight	0.76	0.62	1.01*	1.20*	0.52	0.69	0.63	0.82*	0.43
Waist girth	1.15*	1.17*	1.26*	0.40	0.80*	0.89*	1.30*	0.96*	0.78
Belly circ.	1.01*	0.63	1.38*	0.33	1.29*	0.63	1.50*	0.73	0.38
Bust chest girth	1.03*	1.66*	1.30*	0.28	2.15*	1.37*	0.73	0.94*	0.82*
Buttock girth	0.90*	1.91*	1.19*	0.48	0.56	0.90*	1.34*	1.03*	1.57*
High hip girth	0.95*	0.52	1.44*	0.34	1.32*	0.56	1.41*	0.94*	0.28
High waist girth	1.23*	1.33*	1.17*	0.50	0.59	0.90*	1.07*	0.84*	0.80*
Hip girth	0.95*	1.97*	1.21*	0.32	0.53	0.99*	1.42*	1.34*	1.58*
Middle hip	0.89*	0.55	1.59*	0.48	1.28*	0.51	0.88*	1.26*	0.70
Torso width waist	2.39*	1.19*	1.11*	0.53	1.39*	2.02*	1.00*	0.98*	0.76
Under bust circ.	1.05*	1.62*	1.39*	0.58	2.36*	0.74	0.82*	0.97*	0.84*
Waistband	0.88*	1.09*	1.27*	0.41	0.93*	1.03*	0.79	1.48*	0.74
Distance neck - hip	0.63	0.56	0.31	0.71	0.51	1.16*	0.83*	1.23*	1.33*
Side upper torso (L)	0.49	0.52	0.53	0.49	0.87*	0.37	0.49	0.39	0.80*
Side upper torso (R)	0.47	0.54	0.50	1.54*	0.79	0.55	0.49	0.52	0.71
Cross shoulder	0.76	0.73	1.11*	0.50	1.07*	0.76	0.56	0.60	0.37
Across front width	0.67	0.70	0.86*	0.54	0.93*	0.41	0.57	0.70	0.72
Width armpits	1.30*	0.98*	0.90*	0.83*	1.39*	0.60	0.47	0.54	0.20
Across back width	0.87*	0.85*	1.13*	0.65	1.02*	0.82*	0.60	0.71	1.11*
Neck - waist distance	0.51	0.40	0.50	0.81*	0.88*	0.83*	0.64	0.51	1.01*
Neck left - waist back	0.59	0.41	0.52	1.07*	0.96*	1.01*	0.62	0.63	0.94*
Neck right - waist back	0.68	0.54	0.52	0.81*	0.90*	1.03*	0.60	0.47	0.93*
Across back width	0.56	0.54	0.32	0.55	0.69	0.65	0.76	0.44	1.24*
Waist - high hip back	0.53	0.40	0.40	0.92*	0.48	1.21*	0.80*	1.21*	0.59
Waist - buttock	1.56*	1.39*	0.75	1.49*	0.50	1.59*	0.88*	1.24*	1.34*
Waistband - buttock	1.19*	1.65*	1.30*	0.81*	0.81*	1.87*	1.24*	1.54*	2.14*
Crotch length	1.01*	0.57	1.25*	0.33	0.64	0.55	1.29*	0.78	0.80*
Crotch length front	0.91*	0.59	1.21*	0.80*	0.71	0.65	1.42*	1.33*	1.72*
Crotch length rear	1.45*	0.94*	1.15*	0.97*	0.70	0.53	1.26*	1.31*	0.86*
Waist - buttock (L)	0.64	0.60	0.50	2.80*	0.41	1.23*	0.79	1.13*	0.55
Waist - buttock (R)	0.66	0.66	0.54	2.65*	0.43	1.21*	0.79	1.20*	0.61
Waistband-buttock (L)	1.04*	1.02*	0.67	1.04*	0.75	1.00*	1.48*	0.91*	1.28*
Waistband-buttock (R)	1.05*	1.06*	0.69	0.58	0.78	1.02*	1.52*	1.10*	1.29*
Torso length	0.84*	0.50	0.54	1.17*	0.59	1.14*	1.00*	1.41*	0.50

*Variable importance in projection (VIP) values ≥ 0.8 (marked in grey fields).

Figure 4a presents the predicted (allometric) variations in the first 9 torso shape principal components corresponding to unit changes in torso size measures. There are strong allometric relationships between torso size and shape PC's 1, 2 and 3, with these features changing significantly with increases in torso size. Figure 4b displays the predicted torso shapes for individuals with the smallest (68 cm), mean (110 cm) and largest (152 cm) measured waist girth values within the LIFE-Adult cohort. Increases in torso size appear to correspond with increased mass and curvature on the anterior aspect of the torso segment.

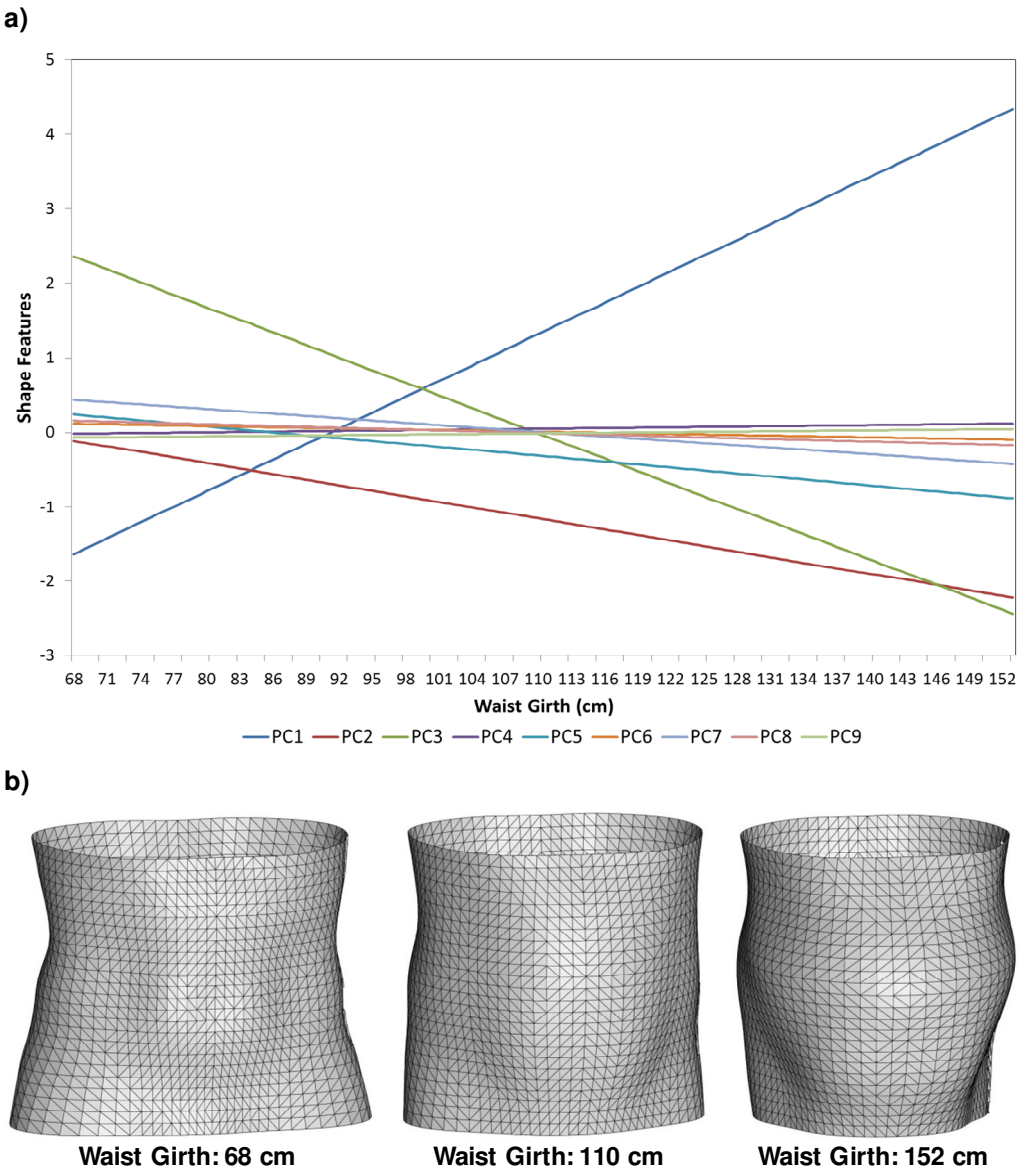

Fig. 4. Allometric relationships between torso size and shape measures. a) Predicted changes in shape features using PLSR models according to dependence on waist girth; b) Predicted torso shape for males with waist girths of 68, 110 and 152 cm.

4. Discussion

Allometry is the study of size-related changes in morphological traits and is commonly used to assess biological scaling relationships within species [31]. The aim of this study was to investigate allometry between traditional measures of human body size and novel measures of body shape, obtained using 3D imaging and geometric morphometrics. Anthropometric investigations which have previously utilised 3D imaging to acquire dimensions of the human body have only obtained measures of body size, or simple shape variables based on combinations of body girths, to analyse variations within a population [10,20,22]. Though this approach enables a thorough characterisation of body size, it discards body shape information and morphological traits captured by 3D imaging systems. As a result, it has limited the discipline of anthropometry to only consider relationships between measures of body size and derived indices, without considering relationships between size and shape, which may reveal additional information. In contrast, the approach used in this study has identified subtle, scale-invariant morphological features that characterise deviations in torso shape within a large population-based cohort, which cannot be captured using traditional anthropometric techniques.

There have been recent investigations which have also utilised statistical methods, such as PCA, to identify features of torso shape variation directly from 3D imaging data [39,47,48]. This approach quantifies the extent to which measures of body size and shape are independent of each other, thus, it follows to investigate whether they are related or provide complementary information. These studies have typically used Pearson's correlation coefficients to determine whether there are linear relationships between principal components of torso shape variation and individual measures of body size. However, assessing correlations between individual size measures and shape principal components in this way is limited, in that the complex, scale-invariant features identified by PCA, such as curvatures and external contours, may not be dependent on changes in individual one-dimensional measures, such as lengths or girths. In contrast, geometric morphometric studies typically utilise multivariate regression analyses to evaluate allometric scaling between size and shape and have found that allometry can account for large proportions of shape variation, due to body composition and genetic variability within species [31–33]. Our results agree with these previous studies of allometry, since strong relationships were observed between combinations of torso size measures and shape, suggesting that size-related changes are a dominant factor contributing to morphological variation in humans. For example, torso size measures explained over 50% of the variation in each of shape PC's 1, 2, 3 and 5. Examination of the VIP values for size measures used in the PLSR models, demonstrated that measures of torso girth contributed most to the prediction of shape. This suggests the presence of allometric scaling between torso shape features and changes in torso girths, which could explain why girth measures and their ratios are often used as simple proxies of abdominal shape in practice [20]. Though it is clear that certain features of torso shape do scale with increases in body size, the physiological mechanisms that underlie these allometric relationships are not fully understood. We hypothesise that an increase in overall body size corresponds to changes in the deposition of visceral fat around the body which causes changes to external body shape. Further studies are required to establish these relationships. In addition, it has been shown that some principal components of torso shape variation do not scale with changes in size and therefore cannot be explained by allometry. These subtle variations in body shape, which do not scale with body size, could contain additional information regarding distributions in body fat and associated health risks that cannot be identified by measures of human body size currently used in clinical practice. Further studies are required to assess the relative value of these new anthropometric quantities.

Though the LIFE-Adult cohort is one of the largest collections of 3D body scan data currently available, containing participants that represent an extensive range of body shapes and sizes, a limitation of this study was the lack of ethnic diversity. In addition, only 400 participants in the LIFE-Adult cohort are under the age of 40 years old. As such further study is required to assess individuals from a wider range of ages and ethnicities, to determine whether the findings of this investigation are representative of the wider population. Finally, this study only analysed the body scan data and extracted measures of male participants from the LIFE dataset. However, the LIFE dataset contains extensive disease phenotype information of male and female participants, including: metabolic disorders (type 2 diabetes, obesity), cardiovascular disorders and biomarkers of disease progression [2]. Future study is therefore required to investigate relationships that may exist between allometric scaling relationships and underlying disease phenotypes in both males and female individuals.

5. Conclusion

This study demonstrates how novel analytical procedures for characterising variations in human torso shape can identify allometric scaling relationships that exist between measures of torso size and shape within a large population-based cohort of individuals. The aim of future work will be to further investigate the underlying causes of these relationships and whether they differ between population groups.

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